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Wind Turbine Down-regulation Strategy for Minimum Wake Deficit

Kuichao Ma[1], *Student Member*, Jiangsheng Zhu[1], *Student Member*, Mohsen Soltani[1], *Senior Member, IEEE*, Amin Hajizadeh[1], *Senior Member, IEEE* and Zhe Chen[2], *Senior Member, IEEE*

Abstract—**Down-regulation mode of wind turbine is commonly used no matter for the reserve power for supporting ancillary service to the grid, power optimization in wind farm or reducing power loss in the fault condition. It is also a method to protect faulty turbine. A down-regulation strategy based on minimum wake deficit is proposed in this paper, for the power improvement of the downwind turbine in low and medium wind speed region. The main idea is to operate turbine work at an appropriate operating point through rotor speed and torque control. The effectiveness of the strategy is verified by comparing with maximum rotor speed strategy. The result shows that the proposed strategy can improve the power of downwind turbine effectively.**

I. INTRODUCTION

Wind energy is one of the most widely used renewable energy. With the development of wind power technology, the single turbine capacity and percentage in the grid are larger and larger. Nowadays, many grid codes enforce the wind farms to fulfil some requirements including different types of power control such as absolute power limitation, balance control and delta limitation [1]. Therefore, down-regulation is a common operating mode for both single turbine and wind farm. It is also known as derating and curtailment. In addition, the power optimization of wind farm and the protection of faulty component also need turbines to operate in the down-regulation mode. The former considers wake effect to optimize the total power of wind farm by down-regulating upwind turbines; the latter protects the faulty component from further damage by reducing the turbine load.

In the past decades, many researchers concentrated on getting better performance in the normal mode. Down-regulation mode just gets more attention until recent years owing to the rapid development of wind energy. It mainly used to reserve power as ancillary service to support grid. The work in [2] describes and compares three down-regulation strategies. Those are maximum rotor speed, constant rotor speed and constant tip speed ratio respectively. Their benefits and drawbacks are discussed in the article. In [3], the authors analyse and compare the simulation results of these three down-regulation strategies on the power optimization of wind farm. The result shows that constant rotor speed strategy can produce more power. Because its steady state operating point has a smaller thrust coefficient C_t. The research work [4] gives priority to torque control than pitch control in medium and low wind speed. This strategy can decrease the frequency and amplitude of the pitch system. The research in [5] focuses on grid requested down-regulation and gives four objectives of control design. The authors suggest that the down-regulation strategy design should avoid stalling and non-monotonic behaviour. In [6], both centralized and distributed controllers are designed to decrease the fatigue of turbines by varying power reference in the down-regulation mode. In the practical applications, maximum rotor speed is the most widely used method. The benefit is that it can store kinetic energy in the rotor and respond the grid demand rapidly.

However, most of the down-regulation strategies prefer to focus on the dynamic performance of the turbine rather than consider the down-regulation effects in the wind farm. In this paper, two above-mentioned situations are taken into consideration.

One is the power optimization of wind farm. In this situation, traditional Maximum Power Point Tracking (MPPT) of the single turbine cannot reach the maximum power of the whole wind farm because of the wake effects. An effective way to improve the wind farm power is down-regulating upwind turbines to decrease the power loss caused by wake effects [7]. Therefore, down-regulation strategy is an important factor and it will affect the optimization result directly. Appropriate down-regulation strategy for individual turbine can improve the power production of the wind farm [3].

The other situation is that the component of wind turbine is in some fault conditions. For some small faults, the shutdown of the wind turbine will cause the unnecessary production loss. So down-regulation operation is another method to treat some faults. However, it does not mean that all the fault conditions are applicative to this situation. Two conditions must be met. Firstly, further damage of fault can be prevented by down-regulating power, for example, the initial inter-turn short circuit in the generator stator [8]. The other condition is that the severity of the fault mode should be not high. Because the sustained operation with a severe fault will result in the damage of component and even break down other relevant components. At the same time, the power loss caused by down-regulated turbine should be compensated as much as possible. Therefore, an appropriate down-regulation strategy that can improve the power production of the downwind turbine is valuable in the fault condition of turbines.

Based on these two above situations, it is clear that their purposes in common are improving the power production of other turbines in the down-regulation operation. The key to this problem is the relationship of down-regulated turbine and other turbines. In this paper, we use Jensen wake model [9] to describe the aerodynamic interaction between down-regulated turbine and its downwind turbines. It also means that this method can improve the power production of downwind turbines when the down-regulated turbine is located upwind. We propose a down-regulation strategy based on minimum wake deficit to improve power production of downwind turbines by choosing an appropriate steady-state operating point in the low and medium wind speed region.

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[1] K. Ma, J. Zhu, M. Soltani and A. Hazijadeh are with the Department of Energy Technology, Aalborg University, 6700 Esbjerg, Denmark (email: kum, jzh, sms, aha@et.aau.dk).

[2] Z. Che is with the Department of Energy Technology, Aalborg University, 9220 Aalborg, Denmark (email: zch@et.aau.dk).

To illustrate this strategy and verify its effectiveness, Doubly Fed Induction Generator (DFIG) wind turbine model and a wind farm with two 5MW wind turbines are adopted in section II. In section III, we state the idea and detail process of down-regulation strategy. In section IV, the simulation results of proposed down-regulation strategy are compared with the maximum rotor speed down-regulation strategy. Finally, the conclusions are drawn in section V.

II. WIND FARM MODEL

A. DFIG Wind Turbine Model

DFIG is a widely used type of the modern Variable Speed Constant Frequency (VSCF) wind turbine. In this paper, we adopt the steady-state models of the NREL 5MW wind turbine [10]. Because we are trying to reach an appropriate steady-state operating point in down-regulation mode, the transient responses are not considered here. Based on blade element theory, the wind power through the sweep area of rotor blade P_w is calculated as:

$$P_{\mathrm{w}} = \frac{1}{2}\rho\pi R^2 v^3 \tag{1}$$

where ρ is the air density; R is the radius of blade and v is the wind speed. The mechanical power P_m extracted by the turbine is calculated as:

$$P_{\mathrm{m}} = P_{\mathrm{w}} \cdot C_{\mathrm{p}}(\lambda, \beta) \tag{2}$$

where C_p is the power coefficient, which is the function of the tip speed ratio λ and pitch angle β, and commonly expressed as a table or a surface like Fig. 1. The negative parts are set to 0 for better illustration. The tip speed ratio λ is defined as the ratio of blade tip speed over the incoming wind speed and is given by:

$$\lambda = \frac{\omega_{\mathrm{r}} \cdot R}{v} \tag{3}$$

where ω_r is the rotor speed.

For a specific wind turbine, (1) and (2) express that wind speed, tip speed ratio and pitch angle decide the mechanical power together. Fig. 1 shows that the maximum power coefficient is obtained when the pitch angle is 0° and it increases first and then decrease with the increase of tip speed ratio. When the pitch angle and wind speed are fixed, there is always a rotor speed making the power coefficient maximum. It means the rotor speed decides the conversion efficiency of wind energy.

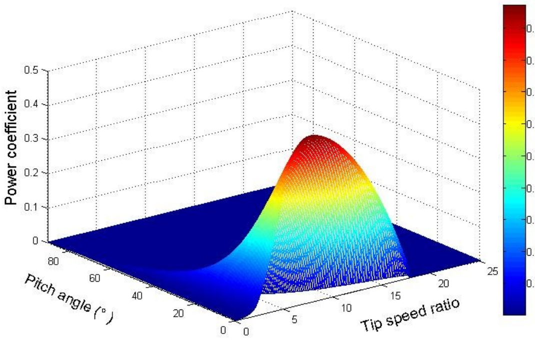

Figure 1. Power coefficient surface

Pitch system is used to adjust the pitch angle of the turbine blade for changing conversion efficiency and supporting aerodynamic brake of the wind turbine. Generation system consists of DFIG and a partial scale power electronic converter (20%–30% of full rating). The active and reactive power can be controlled respectively through changing the rotor current. The rotor speed of the turbine is too slow, so it cannot fit for the speed requirement of DFIG. Therefore, the drivetrain must have a gearbox to provide speed conversion.

B. Wake Model

In wind farms, upwind wind turbines extract energy from wind and cause a wind speed deficit of the downwind turbines because of wake effect. The wind speed deficit will result in the power loss at the same time. Although the upwind turbines can get maximum power, the power loss of downwind turbine will decrease the power production of wind farms. For this reason, the consideration of wake effect for power production in wind farms is important and necessary. In order to describe wake effect accurately, there are many models have been proposed [11]. In this paper, the widely used Jensen wake model is adopted in order to estimate the wind speed deficit of downwind turbines. Fig. 2 indicates the speed relationship between upwind and downwind turbines. The wake deficit equation of wind speed is given by:

$$1 - \frac{v}{u} = \frac{1 - \sqrt{1 - C_{\mathrm{t}}}}{(1 + 2\alpha X / D)^2} \tag{4}$$

where v is the wind speed of downwind turbine; u is the ambient wind speed of upwind turbine; C_t is the thrust coefficient of wind turbine; X is the distance between two turbines; D is the diameter of the rotor, and choosing decay constant α as 0.04 for offshore and 0.075 for onshore wind farms is recommended in [12]. Thrust coefficient surface is shown in Fig. 3. According to (4), the smaller C_t value will lead to the smaller wind speed deficit for a specific wind farm. Based on this relationship, we propose a minimum C_t down-regulation strategy to minimize the wake deficit.

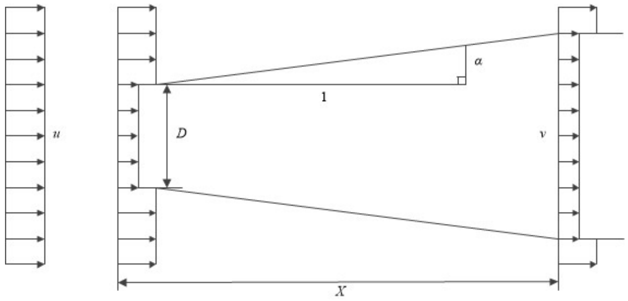

Figure 2. Speed relationship between upwind and downwind turbines in Jensen wake model

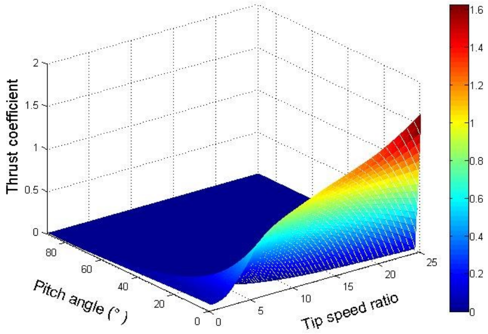

Figure 3. Thrust coefficient surface

C. Wind Farm Layout

To illustrate the proposed down-regulation strategy, a wind farm with two wind turbines in a row is used. The wind direction is set as the down-regulated turbine is in the upwind and downwind turbine is in the full wake of the upwind turbine. The distance between two turbines is $6D$. The wind farm layout is shown in Fig. 4. Wind speeds of upwind and downwind are v_1 and v_2 respectively. We choose the decay constant α as 0.04 here. Then v_2 can be calculated as:

$$v_2 = v_1 \cdot \left(1 - \frac{1-\sqrt{1-C_t}}{1.48^2}\right) \tag{5}$$

where C_t is the thrust coefficient of the down-regulated turbine.

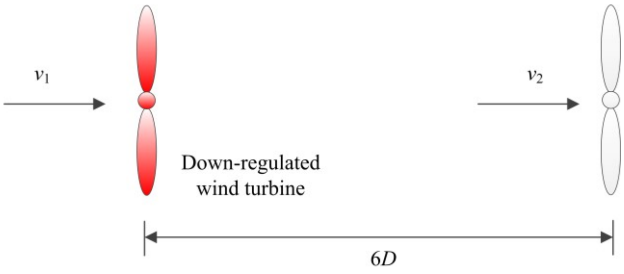

Figure 4. Wind farm layout

III. MINIMUM WAKE DEFICIT DOWN-REGULATION STRATEGY

A. Minimum C_t Operating Point

As mentioned above, C_p represents the conversion efficiency of wind energy. Based on this meaning, we can also calculate C_p by another equation as:

$$C_p = \frac{P_{dem}/\eta}{P_w} \tag{6}$$

where P_{dem} is the power demand of wind turbine; η is the total efficiency of generator and drivetrain.

In down-regulation mode, mechanical power is less than the largest power that turbine can get from wind energy. In other words, down-regulation mode is to decrease the conversion efficiency and get a smaller C_p value than that in the normal mode. Although there are numerous operating points at the same C_p value, there must be an operating point making the C_t value minimum. In Fig. 5, the dark blue line is C_p curve at 0.4. Other colour lines are C_t curves at different operating points. It can be seen that different operating points correspond to different C_t values. The green-circle point is the minimum C_t operating point. If the down-regulated wind turbine operates at this point, the wake deficit will be the smallest.

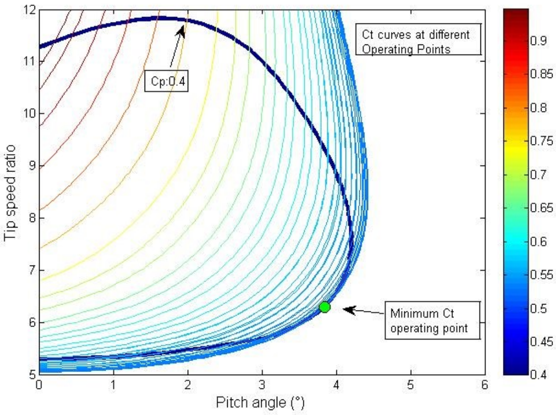

Figure 5. C_p curve with different operating points and C_t values

According to the C_p and C_t surfaces of wind turbine, we can get the minimum C_t operating points on all the C_p curves. It can be formulated as an optimization problem by:

$$\min C_t(\lambda, \beta) \tag{7}$$

Subject to:

$$C_p(\lambda, \beta) = C_{p\_dr} \tag{8}$$

$$\lambda_{min} \le \lambda \le \lambda_{max} \tag{9}$$

$$\beta_{min} \le \beta \le \beta_{max} \tag{10}$$

where C_{p_dr} is the power efficiency at down-regulation mode, calculated by (6); λ_{min}, λ_{max}, β_{min} and β_{max} are the lower limits and upper limits of tip speed ratio and pitch angle.

In Fig. 6, all the green-circle points are the different minimum C_t operating points on C_p curves when C_p value is from 0.1 to 0.4. The corresponding minimum C_t curves are also displayed in the figure.

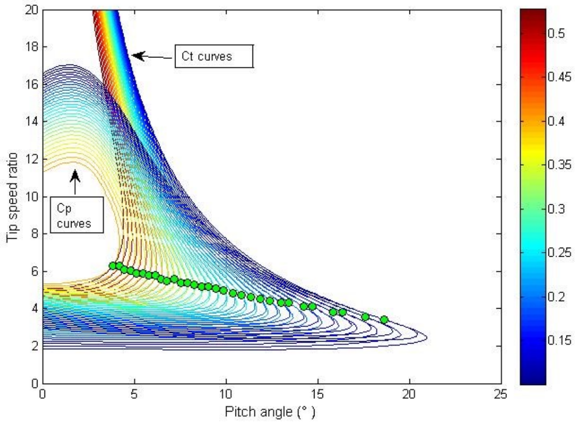

Figure 6. Minimum C_t operating points on C_p curves

B. Process of Down-regulation Strategy

The process of down-regulation strategy includes four steps:

- Down-regulation judgement. Firstly, it is necessary to judge the mode according to the power demand. If power demand divided by efficiency is equal or larger than the maximum mechanical power that wind turbine can get from wind energy, it states wind turbine is running in normal mode. Otherwise, the wind turbine is in down-regulation mode.
- Calculation of C_{p_dr}. This is the power efficiency that the down-regulated wind turbine will operate in. Its value depends on P_{dem}, η and P_w.
- Calculation of rotor speed ω_{r_dr} and pitch angle β_{dr} at minimum C_t operating point. After the calculation of C_{p_dr}, all the operating points need to be found out at this value through the power efficiency surface. Then, the C_t values will be calculated. Here, we use rotor speed instead of tip speed ratio at the specific wind speed. Before choosing the minimum C_t operating point, the limitation of minimum and maximum rotor speed is also needed to be considered. After this, the ω_{r_dr} and β_{dr} are ready to be used in the final step.
- Turbine control. To make the wind turbine operate at the minimum C_t operating point, the reference of generator torque T_{g_ref} is set as:

$$T_{\text{g\_ref}} = \frac{P_{\text{dem}}}{\omega_{\text{r\_dr}}} \tag{11}$$

The reference of rotor speed $\omega_{\text{r\_ref}}$ is set as $\omega_{\text{r\_dr}}$. The $\omega_{\text{r\_ref}}$ is followed by adjusting the pitch angle. According to the $C_{\text{p\_dr}}$ and $\omega_{\text{r\_dr}}$, the pitch angle will approach to β_{dr}.

The flowchart of the proposed down-regulation strategy is shown in Fig. 7.

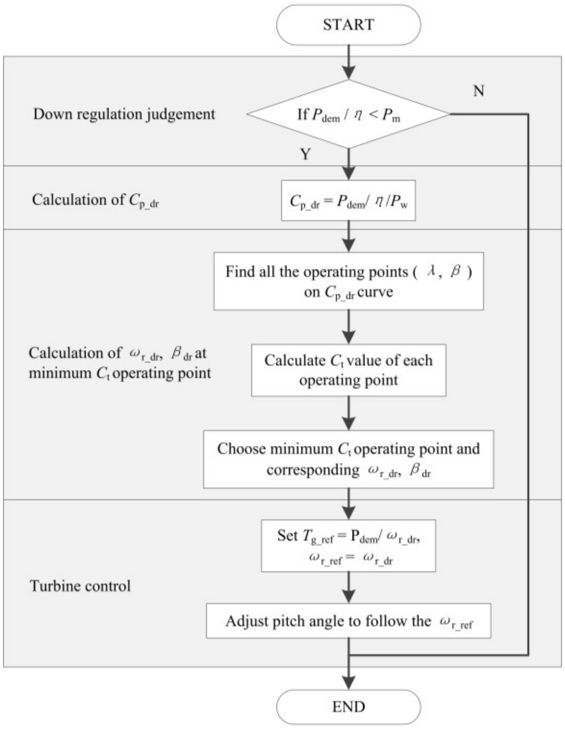

Figure 7. Flowchart of Minimum C_{t} down-regulation strategy

IV. SIMULATION AND ANALYSIS

To verify the effectiveness of the Minimum C_{t} down-regulation strategy (Min-C_{t}), we use it in the wind farm model mentioned in section II. Maximum rotor speed (Max-ω) is a commonly used strategy. This strategy always keeps rotor speed at the rated value in down-regulation mode. The benefit of this strategy is that a part of wind energy is stored as kinetic energy of rotor and response speed is high when the power reference increases. The parameters of NREL 5MW DFIG wind turbine are in Tab. I.

In the high wind speed region, although the wake effect of the down-regulated turbine decreases the wind speed of the downwind turbine, the downwind turbine can still operate in the rated status as long as the wind speed is higher than rated wind speed. Therefore, advantages of Min-C_{t} strategy are useful in the low and medium wind speed regions. So the wind speed is set as 8m/s in the simulation.

TABLE I. PARAMETERS OF NREL 5MW WIND TURBINE

Parameter	**Value**
Rated Power	5MW
Rotor Diameter	126m
Min. and Max. Rotor Speed	6.9rpm, 12.1rpm
Cut-in, Rated, Cut-out Wind Speed	3m/s, 11.4m/s, 25m/s
Gearbox Ratio	97:1
Synchronous Frequency	50Hz
Electrical Generator Efficiency	94.4%
Number of Pole-pairs	3

The only difference between two simulations is the down-regulation strategy. The downwind turbine keeps operating in normal mode. In case 1, the upwind turbine is down-regulated from 1.79 to 1.43MW (20% down-regulation degree). The simulation result is presented in Tab. II, and the operating points of two strategies are plotted in Fig. 8. From the result, we can see that:

- For down-regulated turbine: The rotor speed is at the rated value in Max-ω strategy. Moreover, the operating point has a larger C_{t} value. In Min-C_{t} strategy, wind turbine works at the Min-C_{t} operating point and has the smallest C_{t} value. Compared with Max-ω strategy, it has a larger pitch angle and smaller rotor speed. Because the powers are the same, the generator torque will also be larger.
- For downwind turbine: Compared with Max-ω strategy, the downwind wind speed v_{down} increases from 6.72 to 6.91 m/s. The power improvement $\Delta P\%$ is 9.09%. The power of downwind turbine P_{down} is improved from 0.99 to 1.08MW in Min-C_{t} strategy.

TABLE II. SIMULATION RESULTS IN CASE 1

Variables	**Max-ω strategy**	**Min-C_{t} strategy**
P	1.43MW	1.43MW
β	3.85°	4.21°
ω_{r}	1.2671rad/s	0.7882rad/s
C_{p}	0.3891	0.3884
C_{t}	0.5775	0.5074
T_{g}	12.3kN	19.9kN
v_{down}	6.72m/s	6.91m/s
P_{down}	0.99MW	1.08MW
$\Delta P\%$	9.09%	

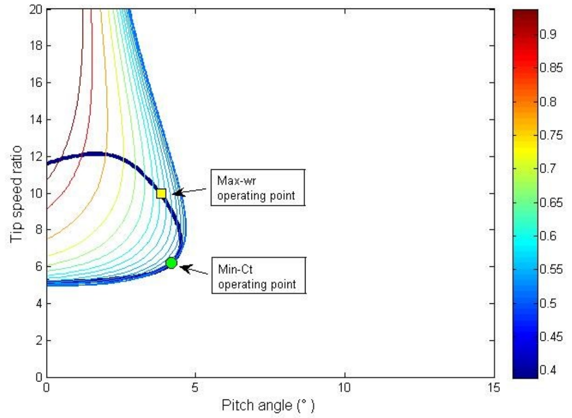

Figure 8. Operating points in case 1

As similar to case 1, the upwind turbine is down-regulated from 1.79 to 1MW (42% down-regulation degree) in case 2. The simulation result is presented in Tab. III. The operating points of two strategies are plotted in Fig. 9.

TABLE III. SIMULATION RESULTS IN CASE 2

Variables	**Max-ω strategy**	**Min-C_{t} strategy**
P	1MW	1MW
β	5.61°	8.12°
ω_{r}	1.2671rad/s	0.7234rad/s
C_{p}	0.2727	0.2702
C_{t}	0.3907	0.3281
T_{g}	8.6kN	15.1kN
v_{down}	7.63m/s	7.69m/s
P_{down}	1.23MW	1.30MW
$\Delta P\%$	5.69%	

From the simulation results, we can get that the wake deficit from the upwind down-regulated turbine is reduced, and the power of downwind turbine is improved in Min-C_t strategy compared with Max-ω strategy. Meanwhile, the torque is higher. The results of case 1 and 2 also prove that the effect of power improvement is related to the degree of increased wind speed.

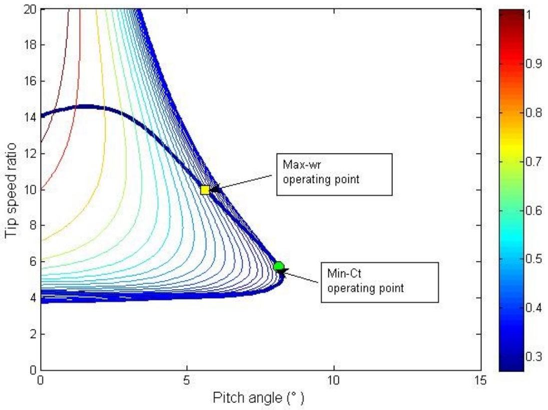

Figure 9. Operating points in case 2

V. CONCLUSION

In this paper, a Min-C_t down-regulation strategy is proposed to improve the power of downwind turbine by reducing the wake deficit from the upwind down-regulated turbine in power optimization and fault condition situations. The simulation results of the wind farm prove that this strategy can make down-regulated turbine work at an appropriate operating point to get the minimum C_t value by the combination of rotor speed and torque control. The wind speed of the downwind turbine is increased. In other words, the downwind turbine can produce more power through this strategy. For the larger wind farm, the influence of this strategy will be significant.

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